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HIGH PERFORMANCE JOINTING SYSTEMS FOR TIMBER

NOT THE FINAL VERSION

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ABSTRACT

In current timber design member sizes are often determined by the need to have an adequate section size for jointing. The use of high performance jointing systems has the potential to achieve substantial reductions in the volume of timber used in conventional structures such as roof trusses. In this programme four different jointing systems which are suitable for large timber sections have been tested: Standard black bolts, Split ring/shear plates, resin bonded steel dowels and butt joints with uni-axial

glass reinforcement. The results have shown that the shear plates and the glass reinforced joints offered the best performance.

INTRODUCTION.

Timber is an excellent construction material with a strength-to-weight ratio comparable with steel. It has considerable environmental advantages over other materials in common use. It is the only material that is a renewable resource and it has low energy consumption in its conversion. However, its use to date in the construction industry has been hampered by the weakness of the jointing systems used.

A number of different jointing systems exist for large timber structures ranging from laterally loaded dowel-types to a range of timber-connectors and those employing structural adhesives. In this programme four different systems were investigated:

- Standard black bolts
- Resin-bonded steel dowels
- Shear-plate connectors
- Butt joint with bonded uni-axial glass (GRP) reinforcement

The first three of these connectors have seen widespread use for large timber members and a substantial amount of work has been performed . The GRP joint is not currently a commercial system but GRP-wood composite techniques are used extensively in boat building.

Research Significance

The aim of this paper is to present results showing the comparative performance of the four types of joint. The aim of the reported experimental work is to show the relative strength and stiffness of the four jointing systems when used on the same simple joint configuration. The application and relative merits of the joints are discussed with particular reference to the GRP system which is not yet used in industry.

It is intended that this work should contribute to the material available to design Engineers when selecting joint types for use with large timber sections in structures such as large span roofs.

Literature Review

Several state-of-the-art reviews of mechanically fastened jointing systems have been performed, usually as a result of the introduction of new design codes that rely on existing research data.

The first significant review was performed by Perkins et al. (1) during which the mode of action of a wide range of timber connectors was established. The American Society of Civil Engineers (ASCE) provided a much needed up-to-date review which details the design rules, and supporting research, of timber joint design in the USA, Canada and UK (2).

UK timber design is currently going through a major period of change as a result of the introduction of EC5 and BS 5268: Part 1, both limit state design codes rather than the permissible stress approach used by BS 5268: Part 2. In anticipation of the introduction of the new codes the Timber Research and Development Association (TRADA) conducted a review (3) of design practice for timber joints and established research data that was needed to support joint design to the new EC5 design code. The review highlighted the general lack of joint embedment response data available which is needed to facilitate joint design to EC5.

In support of the introduction of EC5 and promoting the use of timber within Europe the STEP/EUROFORTECH initiative produced a significant review of timber engineering including jointing systems (Timber Engineering: STEP 1) (4). A similar work is available for US design standards (5).

Dowels and bolts

Trayer (6) performed an extensive research programme into bolted joints involving several wood species and joint configurations. This work formed the basis of the empirical design data for UK permissible stress design codes. Johansen (7) supplemented Trayer's work and developed theoretical equations for predicting the yield load and ultimate load of doweled joints. Whale and Smith (8) extended this work by performing an extensive testing programme into the load-embedment response of doweled joints. They concluded that there was a good correlation between the embedment response and density of wood. Other workers (9,10,11) have used a similar experimental technique which has since been integrated into current testing standards adopted for this research programme.

Rodd et al. (9,12) established relationships between wood density and embedment strength of resin-injected dowels in softwood and hardwood tested both parallel and perpendicular to the grain. Comparisons between resin-injected and plain dowels showed significant improvement in load-slip performance.

Shear-plate connectors

Scholten (13) performed an extensive series of tests on toothed-plate, split-ring and shear-plate connections, the results of which formed the basis of empirical design codes such as BS 5268. Blaß et al. (14) summarised an extensive testing programme of over 900 split-ring and shear plate connector joints and develop design equations for EC5.

GRP reinforced joints

Glued timber joints have traditionally been limited to carpentry joints and finger, scarf or lap joints used in laminated timber products such as glulam. Jausin et al. (15) found that the stiffness of gluelines in finger joints was dependent upon the ratio of the elastic modulus of the adhesive to the thickness of the glueline and that a relatively stiff glueline gave rise to high stress concentrations in the finger-joint.

Although studies have been undertaken on the potential use of glass and carbon-fibre as reinforcement for timber beams (16) there appears to be little published evidence of their use in timber joints other than as glued-in dowels used in the restoration of damaged beam ends.

LABORATORY TESTING PROGRAMME

SAMPLE PREPARATION

The timber was rough sawn, visually graded Special Structural, European Whitewood obtained from a local timber merchant with nominal cross-section 150 × 50 mm. Suitable test samples were selected from this stock based on a further visual inspection for large defects such as splits, knots and resin pockets.

The wood was stored at approximately 20 ± 2°C and 60 ± 10% relative humidity for 3 weeks before joint fabrication and assembly. No attempt was made to condition the samples down to the same moisture content. In all cases the accuracy of cutting/planing was d ± 1 mm for d < 100 mm and d ± 5 mm for d > 100 mm.

After the conditioning period the specimens were sawn and planed.. The sample length varied according to the joint type being tested. Care was taken to ensure that no knots, splits or resin pockets coincided with the positions of the fasteners in the full-size pieces. The slope of grain in the vicinity of the test joint was monitored using a scribe and any samples which exhibited a significant deviation were rejected.

TESTING PROCEDURE

To facilitate a simplified comparison between the mechanically fastened jointing systems a 'standardised' joint configuration was employed (fig.1). After preliminary testing and investigations it was decided to test the joints in uniaxial tension, loaded parallel to the grain.

The standard cross-section of the wood sample was 100 × 44 mm. This cross-section was used throughout the programme for all joint types. The sample thickness of 44 mm was suitable to ensure that for the bolted and doweled joints the L/D ratio was sufficiently low (3.67) to minimise the effect of fastener bending and produce the desired embedment response in the wood (6). For shear-plate connectors, however, this dimension is not recommended since it induces a splitting, rather than shear failure (14). This would have resulted in a slightly reduced load capacity but this limitation was deemed acceptable given the primary objectives of the research programme. End distances of the fasteners were in accordance with the recommended values of BS 5268, 7D for bolted and resin-injected doweled joints (where D is the diameter of the bolt or dowel) and 140 mm for 67 mm shear-plate connectors.

The tests were performed on a purpose-built loading rig (fig. 2) which was positioned on a strong floor. The samples were positioned between a pair of 17 mm thick steel side plates at the top and bottom of the rig. The test connection was positioned at the top (except for the GRP tests) and various bottom (and top for the GRP) connection configurations were employed to ensure failure of the test connection. The substantial steel side plates were used to ensure that bending of the bolts and dowels in the test connection were minimised, thus inducing a consistent embedment response in the wood facilitating a comparison of the joint failures which were due to the wood, rather than the geometrical configuration of the connection.

The tests were conducted in accordance with BS EN 26891. This involves a multi-stage loading regime, the key elements of which are: initial loading to 40% of the estimated maximum load ($F_{est.}$), approximately the working load, of the joint; removal of load to 10% of $F_{est.}$ and finally loading to failure. The time taken to reach the required loading levels is specified. Consequently, the loading rate is dependent on $F_{est.}$. The load was applied using a hand-operated pump connected to a hydraulic jack with a non-return valve. A typical applied load-time history achieved in practice is shown in fig 5. Estimated maximum loads were either calculated using EC5 for the mechanically fastened joints or based on preliminary test results for the GRP joints. Although BS EN 26891 relates to mechanically fastened joints the test procedure was adopted for the GRP joints in order to facilitate a comparison of the load-deformation response.

Deformations of the joint were recorded with LVDTs (fig.3). Four LVDTs were used to determine the slip (relative movement of the connector) of the joint while four more were used to monitor lateral movement and twisting of the sample/loading rig and longitudinal splitting of the sample above the connector. A nominal pre-load was applied to all samples to take up slack in the system.

The load cell and LVDTs were connected to a PC via a signal conditioning unit and Analogue-to-Digital Converter (ADC). The ADC software recorded values at specified time intervals. Measurements were taken at 5 second intervals giving approximately 150 sets of measurements per test - with each set taking approximately 350 ms to record.

Bolted joints

A 12 mm diameter Grade 8.8 bolt was used to form this joint. The bolt hole was drilled at 13 mm diameter and was positioned to within 1 mm accuracy. Aluminium angle plates were positioned with steel washers on the bolt so that when the nut of the bolt was finger tightened a firm seating was provided for the LVDTs to measure movement of the bolt. Similar angle plates were screwed to the side of the wood sample at the centre line level of the bolt hole to measure the movement of the wood at this level (see fig.3 (a)). The average difference between these measurements then gave the movement of the bolt relative to its starting position, i.e. the slip of the joint The bottom rig connection consisted of 3 no. 16 mm Gr. 8.8 bolts to ensure failure in the test connection.

Resin-injected doweled joints

These joints were formed using 12 mm diameter mild steel bars in a 14 mm diameter hole in the wood sample. The dowels were degreased and sanded with emery paper prior to use. The resin-injection technique involved sealing one end of the joint with plasticine (which also kept the dowel centrally located) and then injecting the resin at the other end from one side of the hole only. This allowed the resin to fill the void without forming air pockets. Visual inspection of the failed joints indicated this method was generally successful but only when the resin was not particularly viscous. The remaining details of the joint are as for the bolted joints, except that the LVDTs that monitored the movement of the dowel were positioned on the underside of the steel side plates (see fig.3 (b)).

Shear-plate connector joints

These joints were formed using 67 mm diameter pressed steel shear-plate connectors with 20 mm Grade 8.8 bolts in 22 mm diameter holes. The LVDTs were positioned as for the bolted joints. The bottom connection consisted of a shear-plate together with 2 no. 16 mm diameter bolts.

GRP reinforced joints

These joints were manufactured using a proprietary uniaxial glass-fibre mat and epoxy resin provided by SP Systems Ltd. of the Isle of Wight. The configuration of the GRP reinforced joints differed to that used for the mechanically fastened joints. In these joints the test connection was formed at the centre of the sample with top and bottom rig connections being formed from a shear-plate and 2 no. 16 mm bolts. The joint configurations tested are shown in fig. 4. The glass was wrapped around the joints. This reduced the risk of delamination of the glass fibre. Three configurations were tested: 150 mm butt; 100 mm and 200 mm scarf. (fig.4)

Movement of the joint was monitored by placing four LVDTs on seating angles screwed to the wood at the level of the GRP, i.e. 100 mm (a) or 150 mm (b-d) away from the notional centre line of the joint. The overall height of the sample was kept to nominally 700 mm as with the mechanically fastened joints.

RESULTS OF THE TESTING PROGRAMME

The laboratory test on the full-size joints gave the load-slip response of the joint. A typical load-slip graph for a bolted joint is shown in fig 5.

The following parameters were obtained from the load-slip response (see fig 5):

$F_{max.}$ - the maximum load in kN achieved by the joint, and the corresponding slip in mm;

K_i - the initial stiffness of the joint in kN/mm, determined from a linear regression analysis[1] of the load-slip response after any initial slip to 0.4 $F_{est.}$;

K_s - the stiffness of the joint in kN/mm, determined from a linear regression analysis[1] of the load-slip response during the reloading stage 0.1 to 0.4 F_{est}.

[1] the vast majority of the linear regression analyses gave r^2 values in the range 0.95 to 1.00, except for the GRP joints.

The results for each of the joint types are presented and discussed in the following sections. A summary of the results is given in Table 1 and the strength and joint stiffness results are presented graphically in fig. 9 and 10 respectively. On these graphs all of the replicate sample results are shown in order to indicate the spread of the data. On figure 9 it should be noted that the stiffness of the GRP joints caused premature failure of the samples away from the joints and thus reduced the apparent strength of the joints.

LOAD-SLIP RESPONSES AND MODES OF FAILURE

Bolted Joints

The bolted joints exhibited a non-linear load-slip response (fig 5) upto a maximum load at which point large deformations occurred corresponding to extensive crushing of the wood fibres along the length of the bolt. The overall mode of failure for all of the joints was longitudinal splitting of the wood above the bolt hole. The high-tensile steel bolts were generally unaffected.

Resin-injected doweled joints

These joints exhibited a stiffer and more linear response (fig 6) upto a yield load. Following further deformation a maximum load was reached that was than that for a bolted joint. All of the mild steel dowels underwent extensive plastic deformation during failure of the joint (fig. 11 (a)). The failure mode of all samples was block shear as shown in fig. 11 (b).

Shear-plate connector joints

These joints exhibited a non-linear response upto maximum load (fig 7). No reduction in load was observed prior to failure unlike the bolted and resin-injected doweled joints. The primary mode of failure was longitudinal splitting

GRP reinforced joints

The load-slip graphs for all of the GRP joints are shown in fig 8. They were very irregular for some samples. This appeared to be the result of large lateral movements (relative to the joint slip) induced by mis-alignment of the sample at the GRP joint. This in turn was due to difficulties in keeping the two halves of the sample in-line while the resin hardened. This problem could be overcome through the use of a rig to maintain the alignment of the joint during fabrication. The maximum load for the joint is taken to be the first load drop which accompanied the start of the delamination/failure of the wood-epoxy bond. A significant number of the failures occurred prematurely at the mechanically fastened rig connection - a good indication of the strength of the GRP joint. This is illustrated by a very brittle load-slip response in fig 8. Where failure occurred at the GRP joint further deformation occurred following the maximum load as the glass-fibre delaminated from the timber.

DISCUSSION

Resin-injected dowels appear to give an increased stiffness relative to bolted joints but minimal, if any, increase in embedment strength. This result is not supported by previous research which shows significant increases in embedment strength. This apparent anomaly can be attributed to the debonding of the resin from the relatively smooth surfaces of the dowel.

The overall trend of the results for the GRP is very impressive with strength and stiffness properties higher than either bolts or resin-injected dowels. The strength of the joints is not as high as the shear-plate connectors but they do show a significantly higher stiffness. A significant number of the GRP joint maximum loads were found to be caused by failure of the combined shear-plate and bolted rig connection at the ends of the joint sample. It is suspected that this was caused by lateral stresses induced by the mis-alignment of the timber at the GRP joint causing eccentric loading at the rig connection. This suspicion is supported by LVDT measurements of lateral movement. This eccentricity did not occur with the shear-plate samples which utilised a similar connection detail. Unfortunately, the slip at maximum load is also significantly less (generally < 1 mm) than that for mechanical fasteners reflecting an undesirable brittle failure mechanism. This poses a restriction on their use which requires further investigation.

The results indicate that wood-glass-epoxy joints may have considerable potential in construction. Even though they were not as strong as a shear-plate connector in this configuration they were stiffer and significantly lighter. Bonded glass and carbon fibre are being used increasingly for structural enhancement of concrete (17) and steel (18) as well as timber (19) giving increased confidence in their performance. The obvious advantage of a bonded system for jointing is that there is no loss of section of the structural member. The glass even offers the potential for local structural enhancement of the member in the region of the joint.

During the construction of the test samples problems were encountered with mis-alignment of the timber members. In terms of the complexity of fabrication the bolted joints were the easiest to produce together with the shear-plate connector, although this joint does require a special cutter. The GRP joints were easier to produce than the resin-injected dowel joints which proved cumbersome due to the injection of the resin and keeping the dowel in position until the resin had hardened. The GRP joints would require the use of an alignment rig if a slow curing resin were used. The practical application of glass-epoxy systems to manufacture in a factory environment would be greatly simplified by the use of pre-impregnated glass and heat cured epoxy systems. These would enable the joint to be made in a single rapid operation. Site use of the system would require dry conditions and, possibly, 48 hours of curing before loading. These disadvantages should be balanced against the relative ease of fabrication and the simple application to complex or mis-aligned joints. The stiffness of the GRP joints would be an advantage for minimising deflection of structures and this is seen as one of its main attributes for boat construction. It could, however, induce stresses in other parts of a system, as occurred in the experiments reported here.

CONCLUSIONS

Resin-injected dowels offer some increase in joint performance relative to bolts but the their performance is well below that of shear plate connectors. GRP joints offer very high stiffness but their potential for high strength might be limited in some applications by their rigidity.

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REFERENCES

1 Perkins, N.S.; Lansdem, P. and Trayer, G.W. 1933. Modern connectors for timber construction. U.S. Department of Agriculture, Forest Service, Washington, D.C., U.S.A..

2 Mechanical connections in wood structures. ASCE Manuals and Reports on Engineering Practice No. 84, ASCE, New York, U.S.A., 1996.

3 Page, A.V. and Mettem, C.J. 1993. Efficient detailing of mechanical joints in engineered timber structures. Research Report 2/93, Timber Research and Development Association, High Wycombe, U.K..

4 Timber Engineering STEP 1. Centrum Hout, The Netherlands, 1995.

5 Wood handbook: Wood as an engineering material. Forest Products Laboratory, U.S. Department of Agriculture, Washington, D.C., U.S.A., 1987.

6 Trayer, G.W. 1932. The bearing strength of wood under bolts. Technical Bulletin 332, , U.S. Department of Agriculture, Washington, D.C., U.S.A..

7 Johansen, K.W. 1949. Theory of timber connections. Int. Assoc. for Bridge and Structural Eng. Publications, Zurich, Switzerland, 9: 249-262.

8 Whale, L.R.J. and Smith, I. 1986. Mechanical timber joints. Research Report 18/86, Timber Research and Development Association, High Wycombe, U.K..

9 Rodd, P.D.; Hilson, B.O. and Spriggs R.A. 1989. Resin injected mechanically fastened timber joints. Proc. 2nd Pacific Timber Eng. Conf., Auckland, N.Z., 1989: 350-357.

10 Erki, M.A. 1991. Modelling the load-slip behaviour of timber joints with mechanical fasteners. Canadian Journal of Civil Engineering, 18(4): 607-616.

11 Church, J.R. and Tew, B.W. 1997. Characterization of bearing strength factors in pegged timber construction. Journal of Structural Engineering, 123(3): 326-332.

12 Rodd, P.D.; Spriggs R.A. and Hilson, B.O. 1991. Prediction of embedment characteristics for laterally loaded resin injected bolts in timber. Proc. Int. Timber Eng. Conf., London, U.K., 1991: 350-357.

13 Scholten, J.A. 1944. Timber-connector joints: their strength and design. Technical Bulletin 865, U.S. Department of Agriculture, Washington, D.C., U.S.A..

14 Blaß, H.J.; Ehlbeck, J. and Schlager, M. 1994. Strength and stiffness of ring and shear-plate connections. Holz als Roh- und Werkstoff (52): 71-76.

15 Jausin, C; Pellicane, P.J. and Gutkowski, R.M. 1995. Finite-element analysis of wood joints. Journal of Materials in Civil Engineering, 7(1): 50-57.

16 Plevris, N. and Triantafillou, T.C. 1992. FRP-Reinforced Wood as Structural Material. Journal of Materials in Civil Engineering, 4(3): 300-317.

17 Farmer N and Gee T. Strengthening with GFRP laminates. Construction Repair, February 1997.

18 Karbhari V M and Shulley S B. Use of composites for rehabilitation of steel structures - Determination of bond durability. ASCE Journal of materials in Civil Engineering. Vol 7 No 4 November 1995.

19 Triantafillou C. Shear reinforcement of wood using FRP materials. ASCE Journal of materials in Civil Engineering. Vol 9 No 2 May 1997.

Captions for Illustrations

Figure 1. Standardised Joint

Figure 2 Loading Rig

Figure 3 Loading rig and LVDT positions for recording movement of:

(a) bolted/shear plate connector

(b) resin-injected doweled joint

Figure 4 GRP-reinforced joint configurations:

(a) 150 mm butt

(b) 100 mm scarf

(c) 200 mm scarf

Figure 5 Typical load-slip response of bolted joint test and identification of calculated test parameters

Figure 6 Typical load-slip response of resin-injected doweled joint test

Figure 7 Typical load-slip response of shear-plate connector joint test

Figure 8 Load-slip responses of GRP joint tests

(a-d) 150 mm butt

(e-g) 100 mm scarf

(h-j) 200 mm scarf

Figure 9 Joint strength results

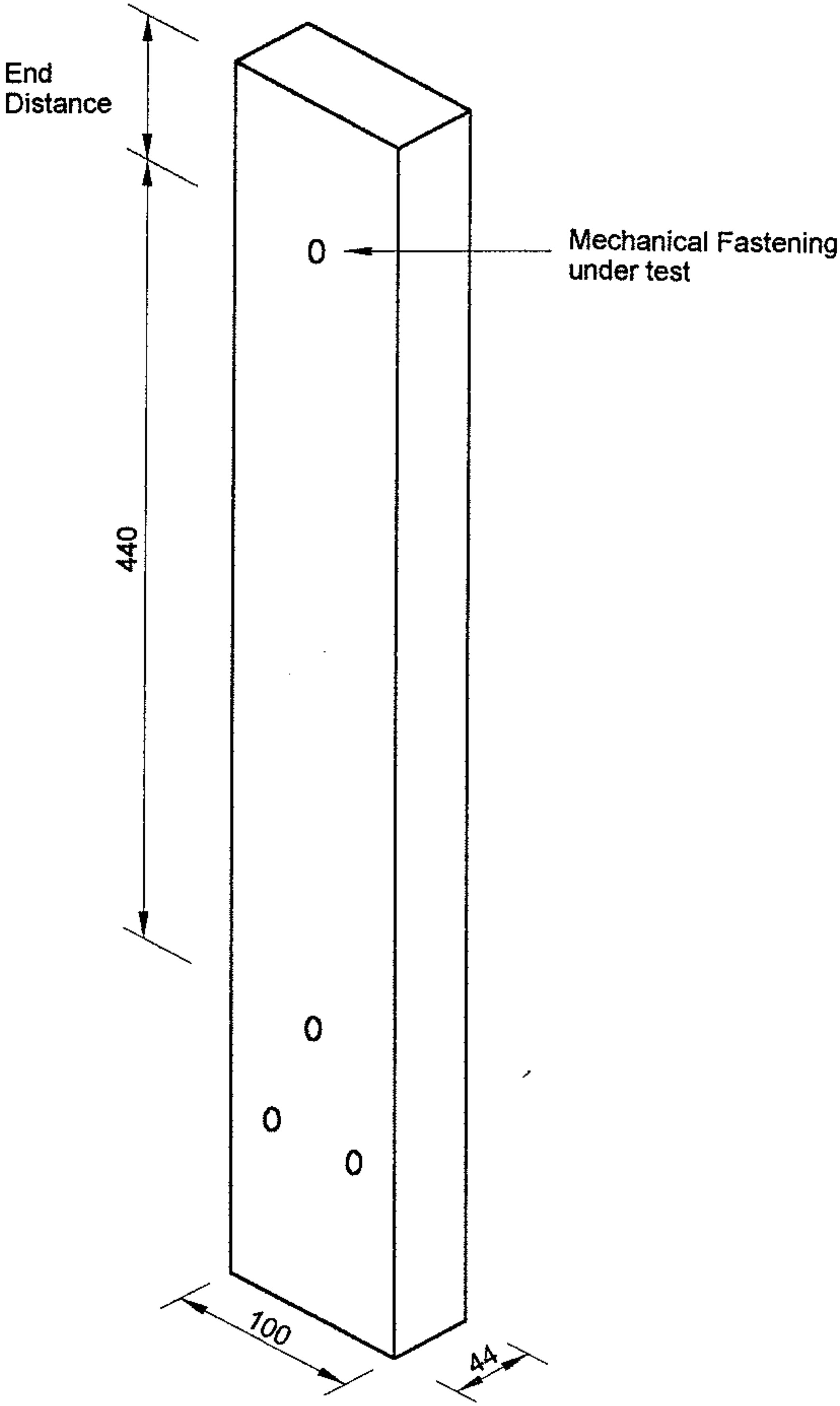
Figure 10 Joint stiffness results,

Initial Stiffness K_i (not shown for GRP samples) and Stiffness K_s

Figure 11 Failure in resin-injected doweled joints

(a) Yielding of dowels

(b) Typical shear failure


End
Distance
Mechanical Fastening
under test
440
100
44

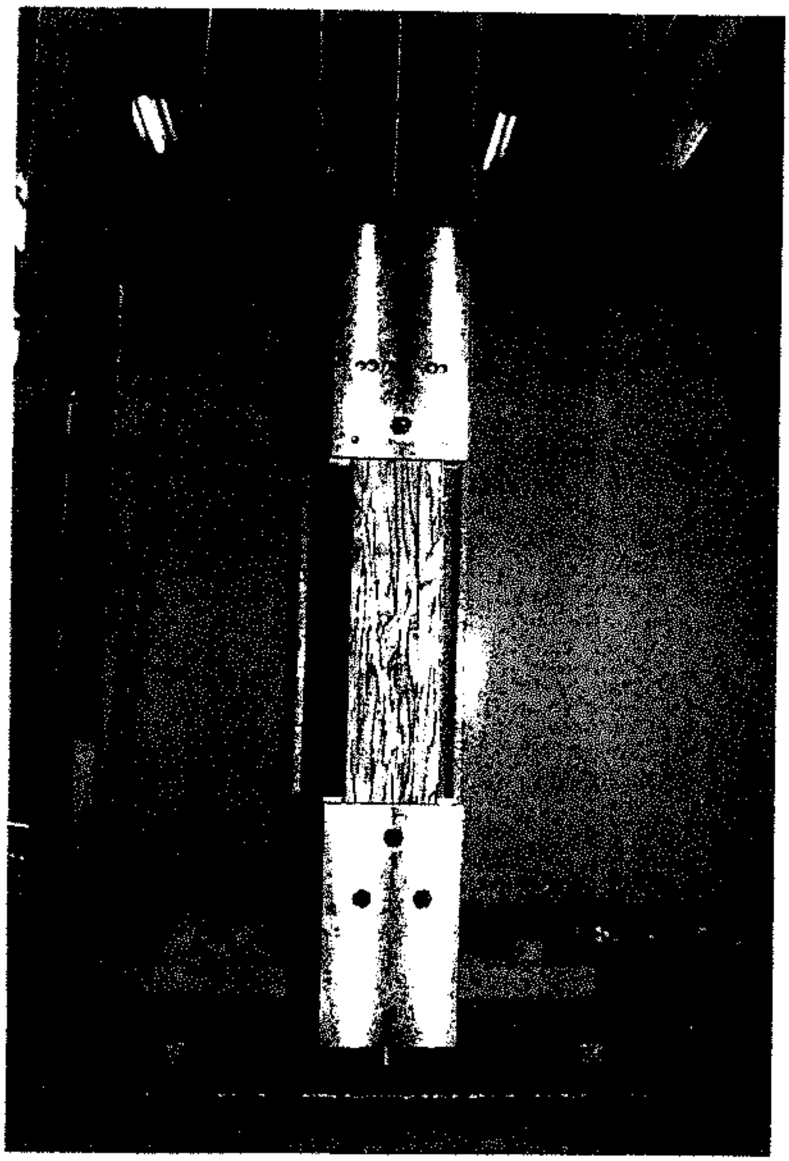


Fig 2

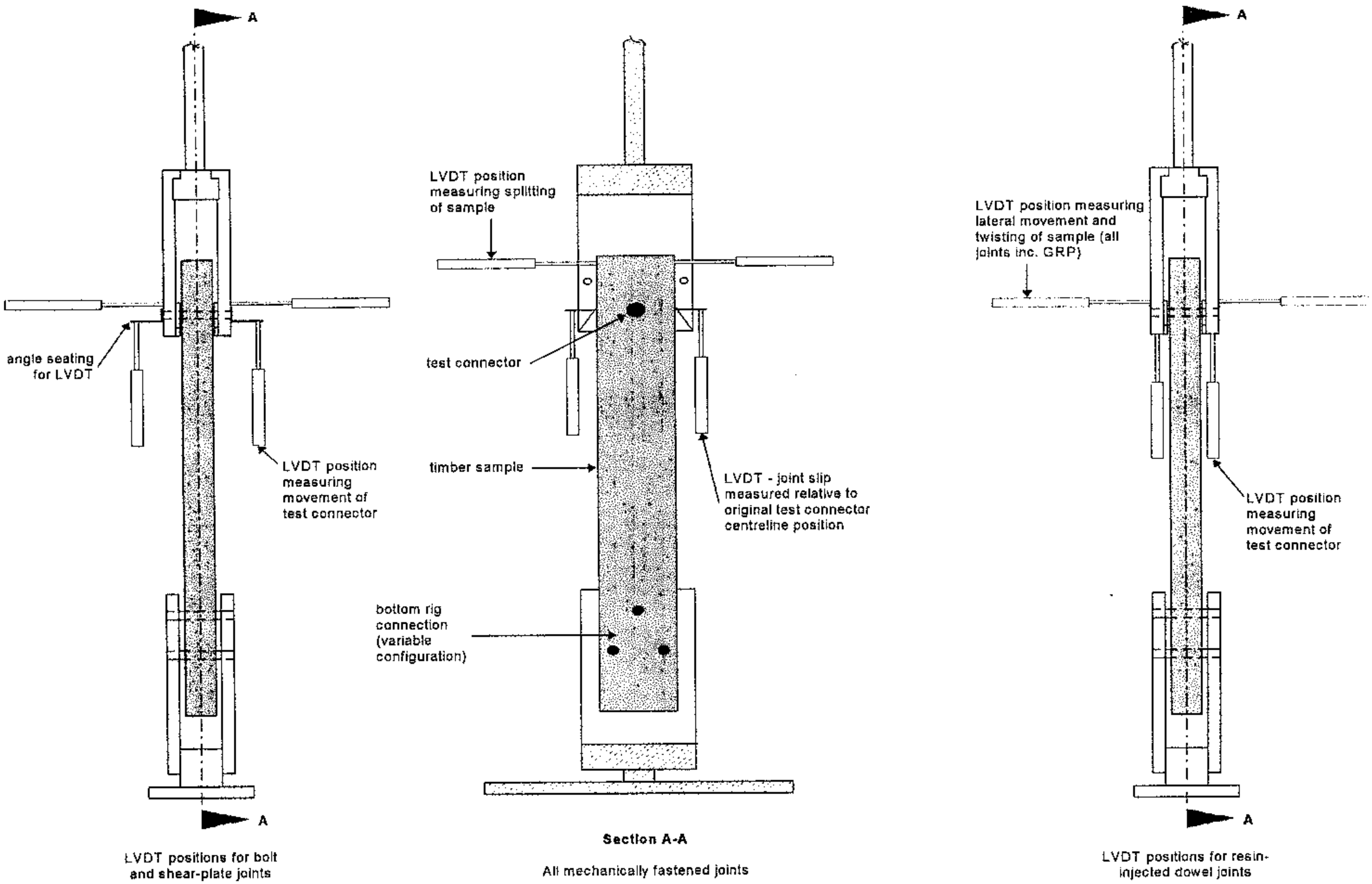
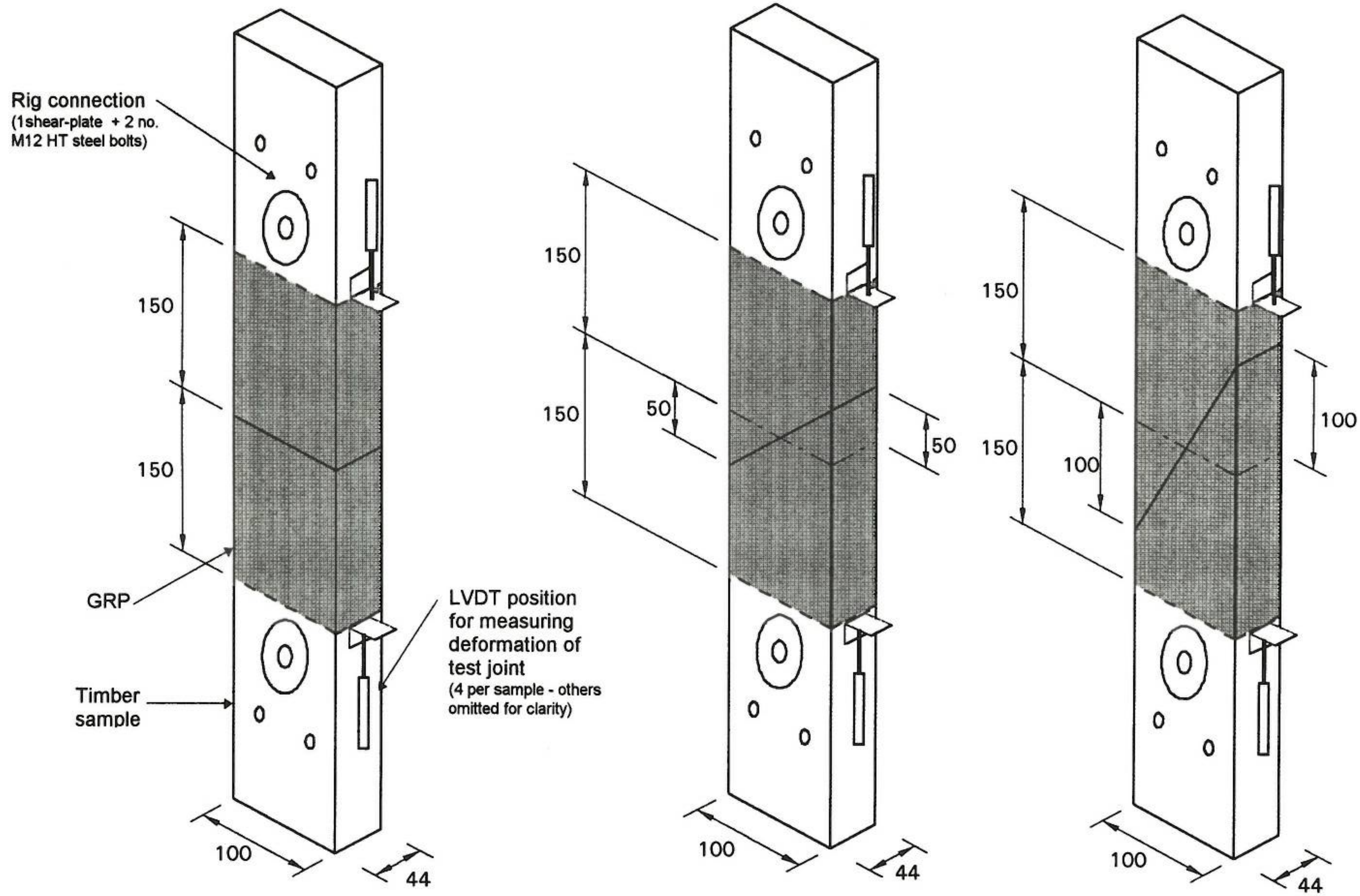

A
A
LVDT position measuring splitting of sample
test connector
timber sample
LVDT - joint slip measured relative to original test connector centreline position
bottom rig connection (variable configuration)
angle seating for LVDT
LVDT position measuring movement of test connector
LVDT position measuring lateral movement and twisting of sample (all joints inc. GRP)
LVDT position measuring movement of test connector
LVDT positions for bolt and shear-plate joints
Section A-A
All mechanically fastened joints
LVDT positions for resin-injected dowel joints

Fig 3.



Rig connection
(1shear-plate + 2 no. M12 HT steel bolts)
150
150
GRP
Timber sample
LVDT position for measuring deformation of test joint
(4 per sample - others omitted for clarity)
100
44
150
150
50
50
100
44
150
150
100
100
100
44

FIG 4

Fig 5

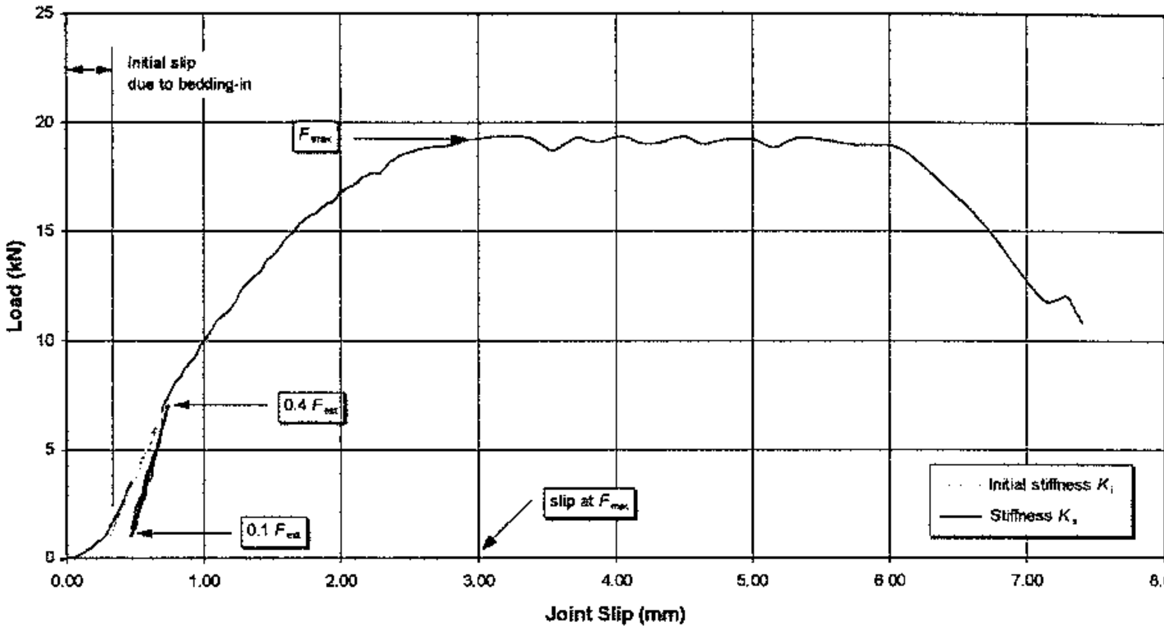


Fig 6

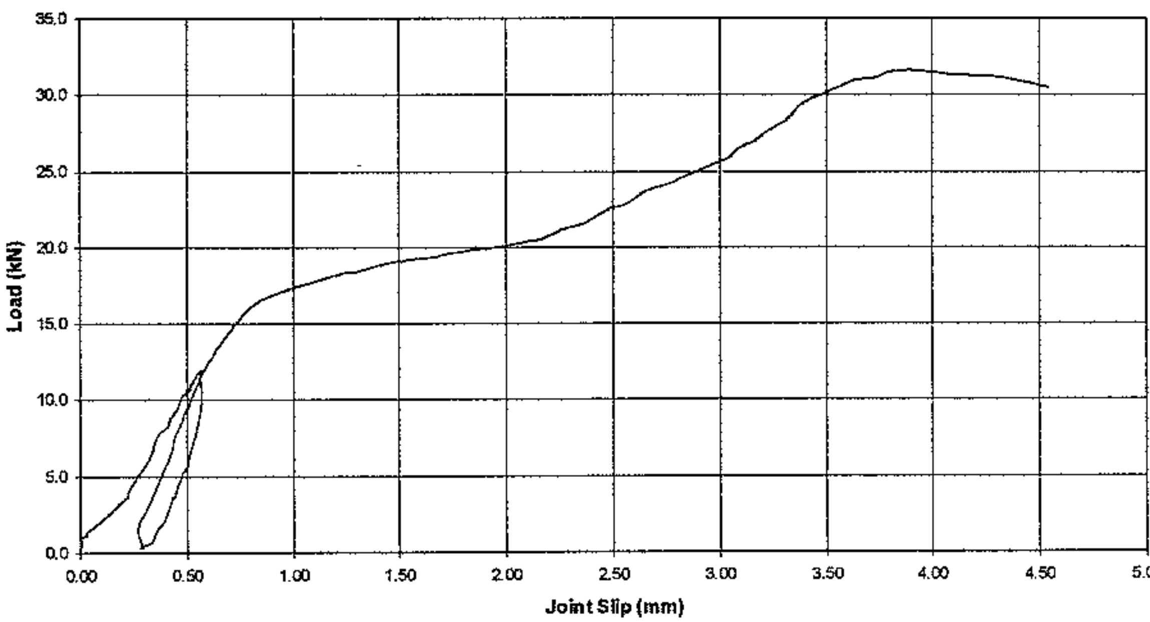
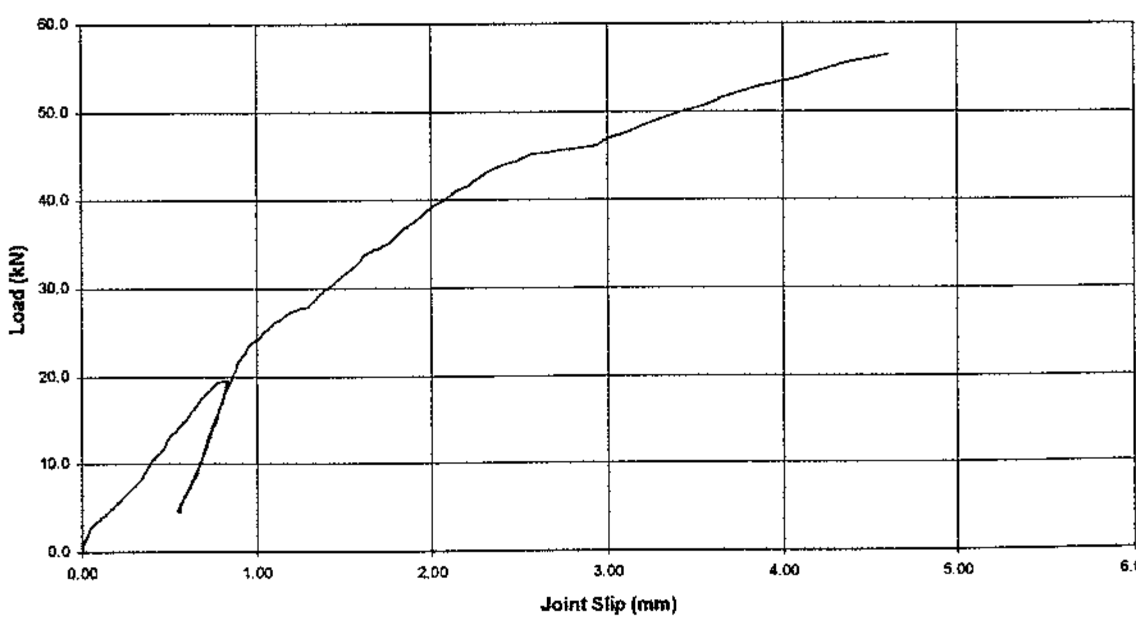
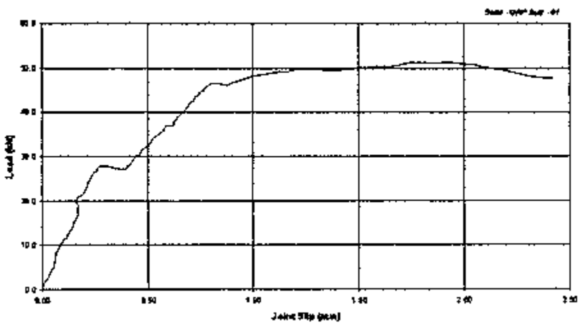
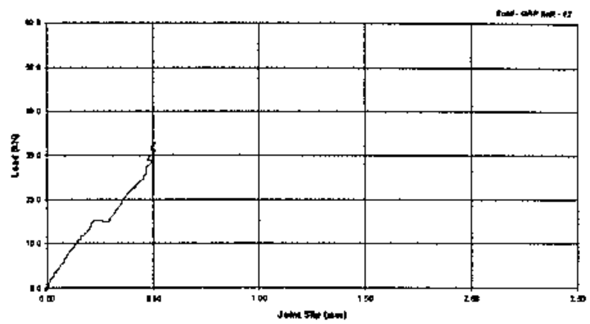
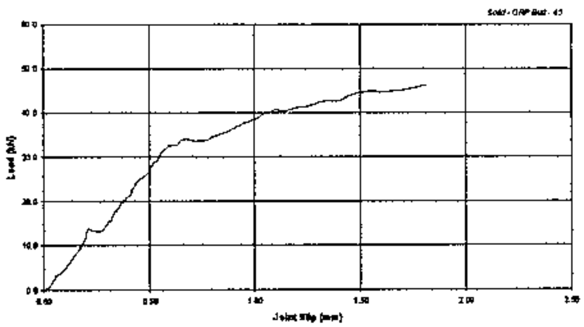


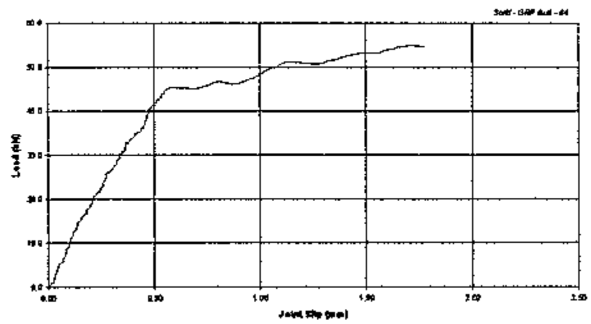
Fig 7

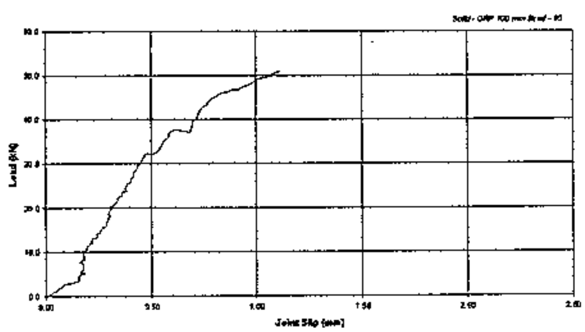


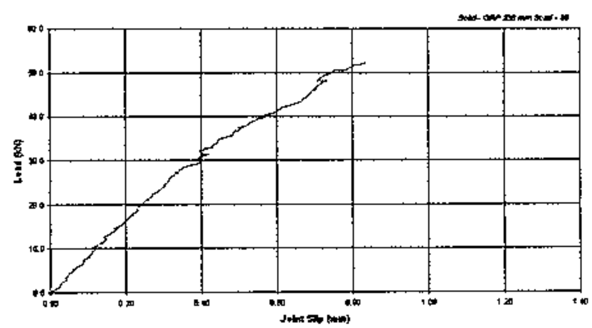

Load (kN)
Joint Slip (mm)

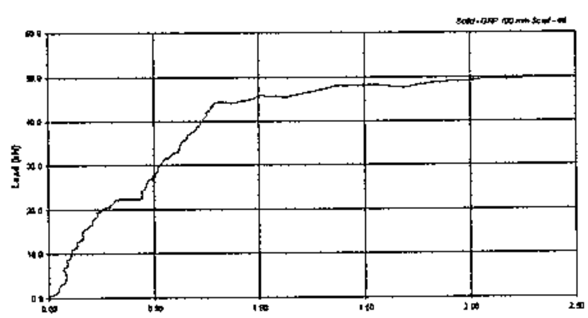

Load (kN)
Joint Slip (mm)


Load (kN)
Joint Slip (mm)


Load (kN)
Joint Slip (mm)


Load (kN)
Joint Slip (mm)


Load (kN)
Joint Slip (mm)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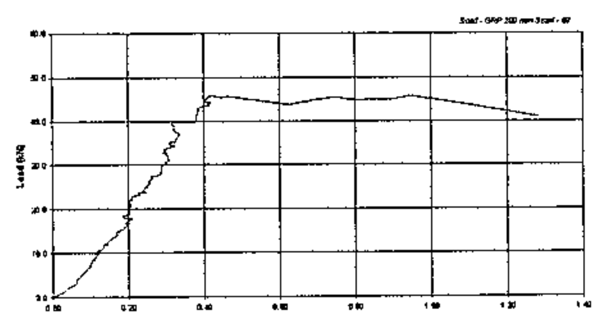
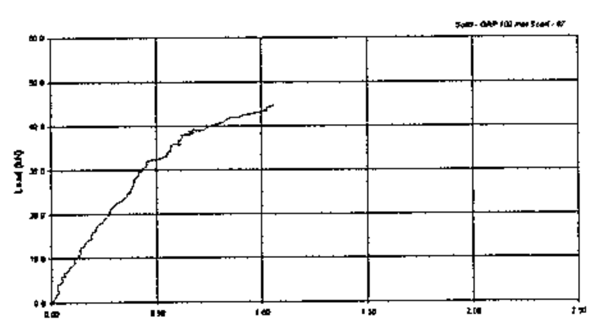
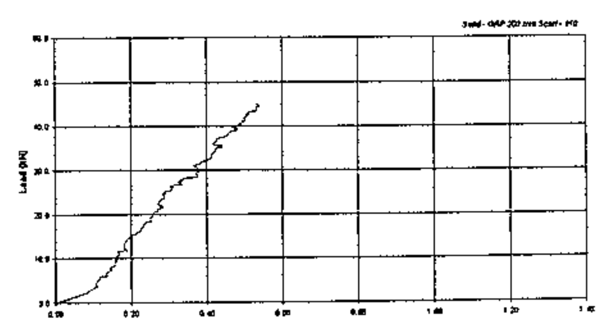
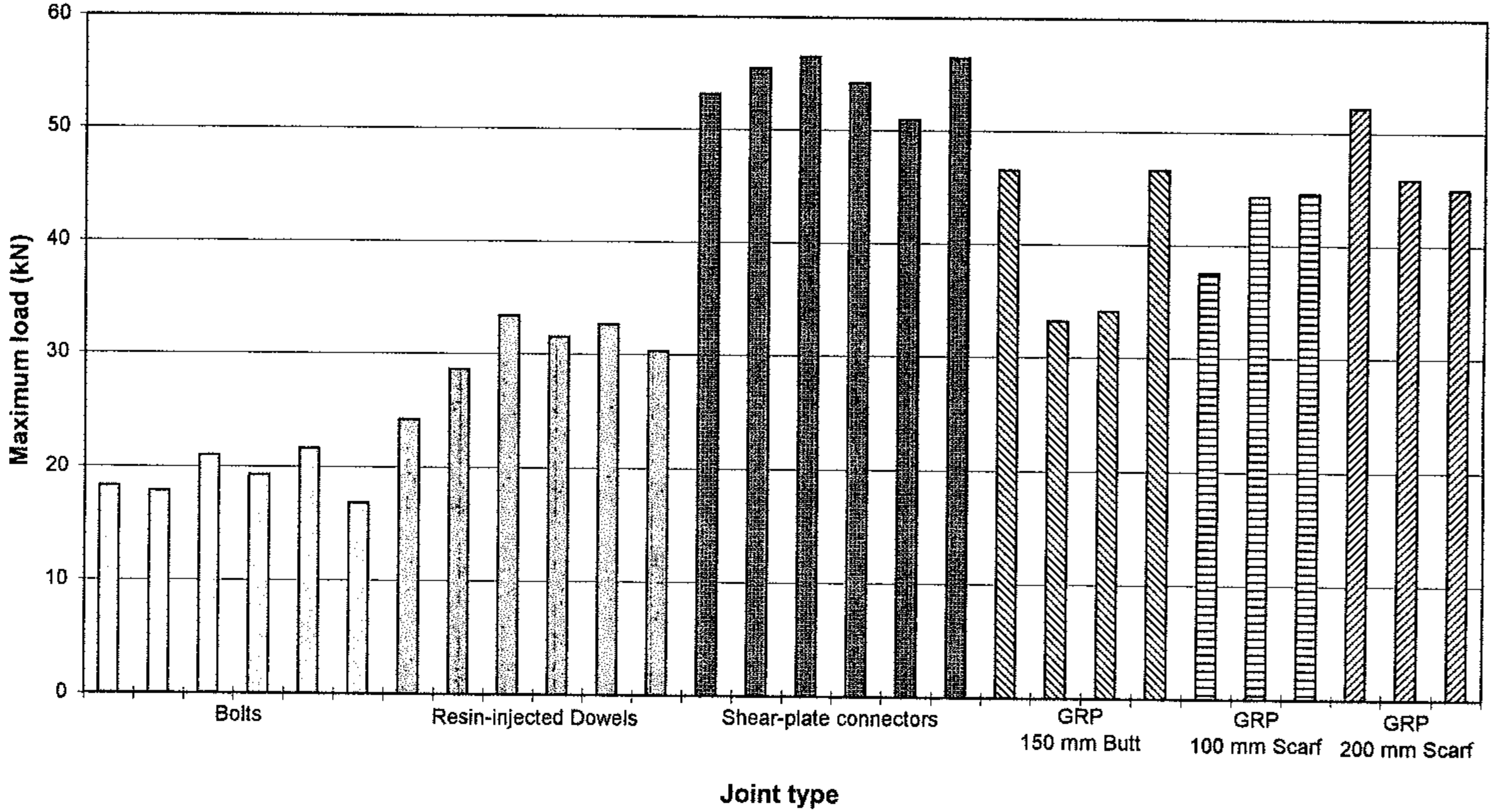
Joint Slip (mm)


Load (kN)
Joint Slip (mm)

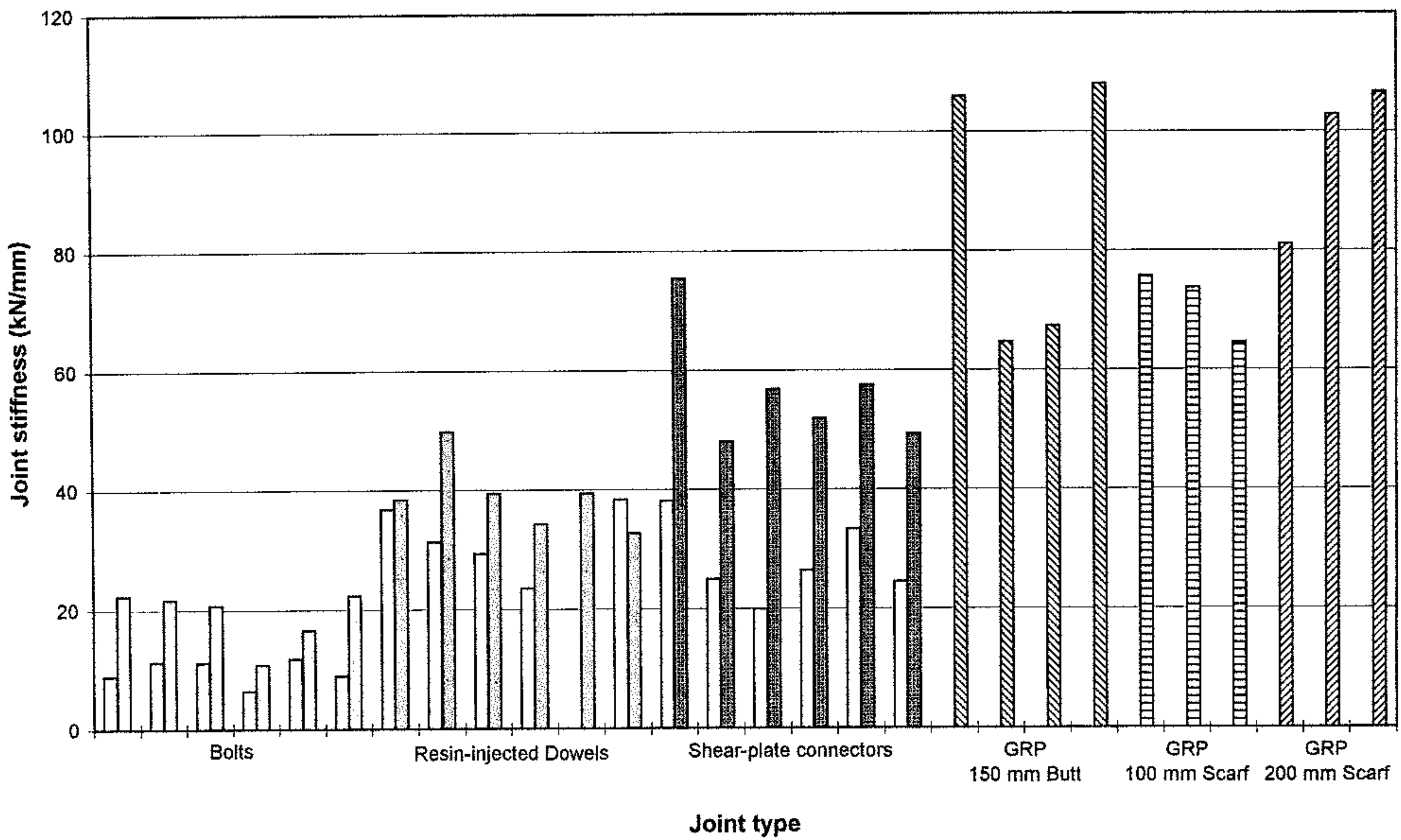

Load (kN)
Joint Slip (mm)


Load (kN)
Joint Slip (mm)



Maximum load (kN)
60
50
40
30
20
10
0
Bolts
Resin-injected Dowels
Shear-plate connectors
GRP
150 mm Butt
GRP
100 mm Scarf
GRP
200 mm Scarf
Joint type

Fig 9.



Joint stiffness (kN/mm)
0
20
40
60
80
100
120
Bolts
Resin-injected Dowels
Shear-plate connectors
GRP
150 mm Butt
GRP
100 mm Scarf
GRP
200 mm Scarf
Joint type

Fig 10.

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